Novel Micromechanical Tunneling Structures for Sensor Applications

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Abstract

Electrostatically controlled micro-cantilevers with integrated tunnel junctions can form the basis of a number of interesting devices with sensor applications. Use of a tunnel junction provides an extremely sensitive way to sense the cantilever position. In its simplest form, the device can be used as a high gain, extremely low power amplifier. If the cantilever were fabricated from a bimetallic strip, it becomes a temperature sensor suitable for use as an pixel element in an infrared focal plane array. Other potential applications include acoustic and seismic sensing. Preliminary cantilever fabrication results will be presented.

Introduction

The invention of the scanning tunneling microscope (STM) [1] brought about the revelation that two electrodes could be mechanically positioned with sufficient accuracy (better than 0.1 nm) to allow electrons to tunnel between the electrodes, and the resulting current could be precisely controlled. Since then, a variety of derivative instruments and techniques have been developed, including the atomic force microscope (AFM). Because the tunneling current is so sensitive to mechanical position, tunneling position sensors have been developed for a variety of purposes. Most relevant to this work is the tunneling accelerometer [2].

Micro-electro mechanical systems (MEMS) technology leverages the integrated circuit industry to build miniature devices, often powered by electrostatic forces, that become more attractive relative to magnetic forces at small dimensions. Electrostatic microrelays have recently been demonstrated [3]. MEMS has also been combined with tunneling junctions to build miniature STMs and accelerometers. Here, we propose the combination of a tunnel junction with a microrelay to produce what may be thought of as a mechanical transistor.

The basic concept of the tunneling microrelay, shown in figure 1, is a simple 3-terminal device with a cantilever that is driven by electrostatic force between the cantilever and the gate. Electrically, it can be compared to the MOSFET, where because the gate potential is capacitively coupled to the conducting channel, there is no DC gate current. To continue the analogy, the other terminals of the device will be designated the source and drain, as shown in the figure. In operation, the gate is biased so that a tunneling current (typically on the order of 1 nA for a tunneling gap of 1 nm) flows between the source and drain. Because the tunneling current is so sensitive to the width of the gap, small changes in the gate voltage will cause large changes in the drain current, so the device exhibits a high gain, or transconductance. Such a device would be linear over small portions of its operating range; it could, therefore, be considered a mechanical analog of a semiconductor transistor, where the input voltage modulates the output current. In this case, however, the input voltage modulates the width of the barrier that the electrons must cross, rather than its height. To continue the analogy, we will next develop a formula for the transconductance, and discuss scaling laws and frequency response.

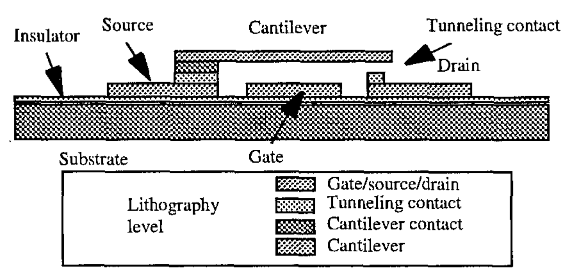

Figure 1. Cross-section through a microrelay device showing the basic structure, as well as the lithography levels, required for fabrication.

Device Theory

Equating the electrostatic force on the cantilever with the restoring force from the cantilever spring gives the equation:

$$Vg = \sqrt{\frac{2k_s \Delta z (z_0 - \Delta z)^2}{\varepsilon A}}, \quad (1)$$

where V_g is the gate voltage, k_s is the spring constant, Δz is the deflection of the cantilever, z_o is the undeflected distance from the cantilever to the gate, and A is the area of the cantilever. From this equation, it is apparent that the gate voltage required for a given deflection reaches a maximum when the cantilever has been deflected to one-third of the total gap between the cantilever and gate. Beyond that point, the cantilever deflection is unstable and snaps the rest of the way closed. Thus, the device can be made hysteretic (or not) by varying the ratio of the gap between the source and drain relative to the gap between the cantilever and gate. Clearly, for the device to operate with stability in the tunneling mode, the source-drain gap must be less than one-third of the cantilever-gate gap. The operation of a real device is considerably more complex, due to issues such as bending of the cantilever and stray fields; nonetheless, this simple analysis seems to capture the essence of the operation of actual devices.

The next step is to incorporate an expression for the tunneling current as a function of the tunneling gap. The tunneling current is proportional to the voltage across the gap, and inversely proportional to the exponential of the gap width:

$$I = V_{ds} K e^{-1.025\sqrt{\phi} w}, \quad (2)$$

where I is the tunneling current, V_{ds} is the source-drain voltage, K is a constant that depends upon the tunneling contact area (with a typical value of 10^{-6}), ϕ is the tunneling barrier height, and w is the tunneling barrier width in Å (which is related to Δz).

By combining these equations, it is possible to derive a fairly simple expression for the overall transconductance per unit current of the microrelay:

$$G_I = \frac{\partial I}{I \partial V_g} = \frac{1}{I}\frac{\partial I}{\partial z}\frac{\partial z}{\partial V_g} = \frac{1.025\sqrt{\Phi} K A \varepsilon V_g}{k z_0^2 \sqrt{1 - \frac{4 A \varepsilon V_g^2}{k z_0^3}}}. \quad (3)$$

Note that, as the deflection required to bring the cantilever into tunneling range increases, the transconductance approaches infinity, reflecting the fact that the cantilever deflection becomes unstable. In practice, thermal noise places a limit on the maximum transconductance that could be achieved. Plugging in some realistic numbers into the equation,

$$I = 1\text{nA}, \quad \frac{\partial I}{\partial z} = 10\text{nA/nm}, \quad \frac{\partial z}{\partial V_g} = 50 \text{ nm/volt}, \quad (4)$$

the result is a transconductance per unit current of 500 V^{-1}. This compares favorably to the bipolar transistor, which has a theoretical maximum value of 40 V^{-1} at room temperature.

Device Design and Scaling Theory

If several microrelays are to be connected together, or if local feedback is used to stabilize the operation of a microrelay (discussed below), V_g must not exceed V_{ds}. Tunneling in air is limited to a maximum of roughly 3 V before irreversible damage occurs to the tunneling junction. In this case, the cantilever must be designed in such a way that it can be deflected to the operational position with just a few volts.

Compared to magnetic forces, the electrostatic force tends to be weak, so for efficient operation it is important to operate the microrelay with the highest electric fields possible (limited by electric breakdown between the gate and the cantilever). This field is typically 10 to 100 V per µm, with the higher value achievable only at the smallest dimensions (e.g., less than 100 nm). In order to achieve optimum operation with a power supply of 3 V, this gate-cantilever gap should not be more than 0.3 µm.

As the device is scaled to smaller physical dimensions, contact sticking between the cantilever and drain becomes a serious issue. At a field of 10 V/µm, the electrostatic force is 440 pNewtons/µm2. The sticking force in a gold-gold microcontact has been measured by atomic force microscope to be 34 nN [4]. For a reasonable margin of error, the relay might need a cantilever restoring force of 100 nN. This translates into a minumum area of 230 μm^2, or a device that is 15 x 15 µm. In turn, this happens to be about the size of the pixels in the digital micromirror device [5], which is very similar to the microrelay.

In a device much smaller than 15 x 15 µm in size, there would be a risk of failure, due to sticking from accidental contact between the cantilever and the drain. Avoiding the sticking problem would require a breakthrough in the materials, some method of amplifying the force (a microlever), or a different method of force production (e.g., magnetic, piezoelectric, thermal). While different force methods have been applied to MEMS, in general, and microrelays, in particular, it seems unlikely that any can be made as small, simple, and low-cost as the electrostatic case. If the sticking force is due to Van der Waals forces, it is doubtful that the choice of materials will have a big impact; the force, however, will be proportional to the area of contact (and the adjacent areas almost in contact). Unfortunately, it will be difficult to fabricate contacts smaller than that already achieved in the AFM. Some part of the force might be due to capillary effects from an adsorbed monolayer of organics or water; operation in UHV might alleviate that effect. Finally, if the sticking is due to microwelding, it is possible that a different material system (e.g., diamond) might prove advantageous, as long as it was sufficiently electrically conductive.

Since the sticking force only occurs over the last few nanometers of device operation, in principle one could tailor the force-verses-distance curves so that most of the force was acting in only in the last few nanometers. One technique that might help would be to place the contact closer to the anchoring point of the cantilever. However, care must be taken that the gap between the cantilever and the drain is sufficient to hold off the maximum operating voltage from source to drain. A more-complicated structure of levers could impart a nonlinear change of the source drain contact distance relative to the gate-cantilever distance, so that the force at the source-drain contact would be by far the greatest just at the point of contact. Again, it seems unlikely that such a device could actually be manufactured.

If the device is scaled by a constant factor in all three dimensions, the resonant frequency will increase proportionately. For a cantilever with dimensions of 10 x 10 x 0.2 μm, the resonant frequency will be on the order of 1 MHz. The resonance frequency would place the upper limit on device operation; in practice, frequencies up to perhaps one-half of the resonance frequency should be possible.

As the cantilever is scaled down in size, thermal mechanical noise will become a more serious issue. For the 10 x 10 x 0.2 μm cantilever operating at room temperature, the size of displacements due to thermal noise would be about 0.04 nm. As the cantilever is scaled down in all three dimensions, the magnitude of the thermal noise would increase by the square root of the scaling factor.

Device Fabrication

The basic process for fabricating the microrelay consists of four lithography levels. The first level defines the gate, source, and drain pads, as well as the interconnect between devices. The second level creates the cantilever-drain tunneling contact, the height of which controls device stability in the tunneling mode, as discussed under device theory. The third level is the cantilever-to-source contact, and the fourth level defines the cantilever. All levels are currently performed by electron-beam lithography, both for fast turnaround time, and tight alignment tolerances. The metallizations are evaporated gold, which provides nonoxidizing electrical contacts. The first two metal levels are patterned by gold liftoff; the wafer is then coated with a polymer resist planarizing layer, which is patterned for the cantilever contacts. The thickness of this polymer layer also determines the separation, z_0, between the cantilever and the gate. More gold is evaporated on top of the resist for the cantilever, which is patterned by argon ion milling through a resist mask. Finally, the polymer planarizing layer under the gold cantilever is removed by an oxygen plasma. Although all individual process steps have been successfully developed, difficulties in integrating them together have so far prevented fabrication of working devices.

Device Operation

For the tunneling relay to operate in a stable fashion, a feedback mechanism will, inevitably, be required to maintain the 1-nm gap required for tunneling. Currently, STMs and other tunneling devices use an external feedback amplifier for this function. Clearly it would defeat many of the advantages of the tunneling microrelay if every microrelay had to be connected to a large, power-hungry amplifier. We propose here a novel self-biasing technique that requires only a resistor for operation (fig. 2). By splitting the gate electrode in half, as shown schematically in figure 2, the appropriate feedback signal can be applied; however, such a scheme has two drawbacks. First, it requires gate voltages needed to operate the cantilever to be less than a few volts, the maximum that can be sustained across a tunnel junction. To simultaneously satisfy this criteria and provide enough force to prevent sticking will require careful device design. Second, the gain of the device is greatly reduced. Essentially, it becomes a voltage amplifier, with a gain determined by the ratio of the size of the input gate to the size of the feedback gate. If required, a third gate could be added, to which a DC bias would be imposed to compensate for variations in device manufacturing.

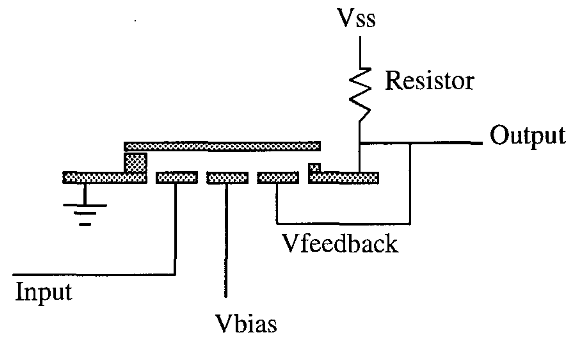

Figure 2. Schematic drawing of a split-gate tunneling microrelay connected as a voltage amplifier, with feedback stabilization.

Sensor Applications

Although circuits based on the microrelay would have a much simpler fabrication process than traditional silicon integrated circuits, it is difficult to imagine microrelays displacing silicon, except in niche applications. These applications would take advantage of some unique feature of the microrelay (e.g., excellent on-off ratio, extremely low power consumption, radiation hardness) and could tolerate microrelay drawbacks (e.g., slow frequency response). One possible application could be a wakeup circuit in an unattented ground sensor, where extremely low power consumption would be a great advantage.

A more interesting possibility is the ability to integrate the sensor as part of the microrelay device. By modifying the cantilever to a bimetallic design, a temperature or infrared sensor can be created. Based on tunneling displacement sensitivities of 0.1 nm and reported sensitivities of bimetallic cantilevers of 60 nm/C, such a device should be able to detect millikelvin temperature changes [6]. In addition, due to the configuration of the sensor, it should be possible to fabricate a two-dimensional focal plane array. By attaching a proof mass to the cantilever, high-performance accelerometers or seismic sensors can be obtained [2]. Finally, the design could be optimized as an acoustic sensor. In particular, by modifying the resonance frequency and Q of the cantilever, a single device could perform the combined functions of detection, filtering, and amplification. Again, such a device might prove very attractive for a wakeup function in an unattended ground sensor.

Conclusion

We presented some novel concepts for a microrelay combined with a tunneling sensor. An analysis of the device's operation shows that the device has a potential for gain (transconductance) exceeding that of semiconductor devices. We defined a fabrication process, and fabricated a number of test devices. We believe that the combination of the microrelay with certain types of sensors has the potential to lead to extremely high-performance, low-cost, low-power applications.

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